Design and construction of various type GRS structures for a new high-speed railway

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ABSTRACT: Due to high-cost effectiveness by low construction cost and high performance in long-term maintenance and against heavy rains, floods and severe earthquakes, various type Geosynthetic-Reinforced Soil (GRS) structures have been constructed for high-speed railways (HSRs), as well as ordinary railways, in place of conventional type ones. An about 66 km-long new HSR line (i.e., Kyushu ShinKanSen Nishi-Kyushu Route) is now under construction to be completed in 2022. To protect the aquatic environment in the adjacent mountain areas, the tunnel level was raised higher, which increased the number of relatively short tunnels, therefore increased the number of elevated structures to be constructed in valleys between tunnels. To meet this and other design conditions, GRS RWs with a total length of 5 km, 80 GRS bridge abutments, 55 GRS tunnel entrance protections and 7 GRS integral bridges, which is densest ever for railways, were adopted. This paper outlines this project.

Keywords: GRS bridge abutment, GRS integral bridge, GRS retaining wall, high-speed railways

1 INTRODUCTION

For High Speed Railways (HSRs) (i.e., ShinKanSen, SKS, in Japanese; Fig. 1), as well as ordinary railways and highways, Geosynthetic-Reinforced Soil (GRS) retaining walls (RWs) with full-height rigid (FHR) facing (Fig. 2) and other type GRS structures have been constructed at 1,178 sites as of June 2017 (Fig. 3a). The total wall length has become more than 170 km (Fig. 3b). The first GRS RW for HSR was constructed in 1991 for Hokuriku SKS. This type of GRS RW is staged-constructed (Fig. 2). First, the backfill is effectively compacted with a help of gravel-filled gabions (or their equivalent) placed at the shoulder of each soil layer. Gravel bags also function as a drain and a mechanical buffer for a completed wall. After a full-height wall is completed then backfill and supporting ground has sufficiently deformed, a FHR facing is constructed by casting-in-place fresh concrete directly on the wall face wrapped around with geogrid reinforcement. In this way, the facing/reinforcement connection is not damaged by differential settlement between the facing and the reinforcement layers during and after construction. Moreover, construction using compressive backfill on a compressive subsoil becomes possible. During casting-in-place, fresh concrete enters the gravel bags through the aperture of wrapping geogrid and geogrid bags. Bi-axial geogrid of PVA is usually used because of its high resistance against high PH environment by concrete, high adhesiveness with concrete and good anchorage in the facing concrete and the backfill. The vertical spacing between the geogrid layers is 30 cm to ensure good backfill compaction in a lift of 15 cm and good integration of the FHR facing to the reinforced backfill. The use of FHR facing ensures not only high durability of the wall face but also high wall stability by: 1) developing high earth pressure on the back of the facing, which results in high confining pressure thereby high stiffness and strength of the backfill; and 2) making the behaviour of reinforced zone monolithic by preventing the development of local excessive deformation and failure planes crossing the facing. Besides, unlike discrete panel facings for GRS RWs and conventional type cantilever RWs, the FHR facing behaves as a continuous beam laterally supported by many geogrid layers. Therefore, large shear forces and moments are not activated in the FHR facing, resulting in a light facing structure, while large overturning moment and lateral thrust forces are not activated at the facing bottom, which usually makes unnecessary the use of a pile foundation.

Moreover, the FHR facing can support noise barrier walls, electric poles and others. Fully taking advantage of this feature, the FHR facing of GRS bridge abutment and GRS integral bridge directly supports a girder.

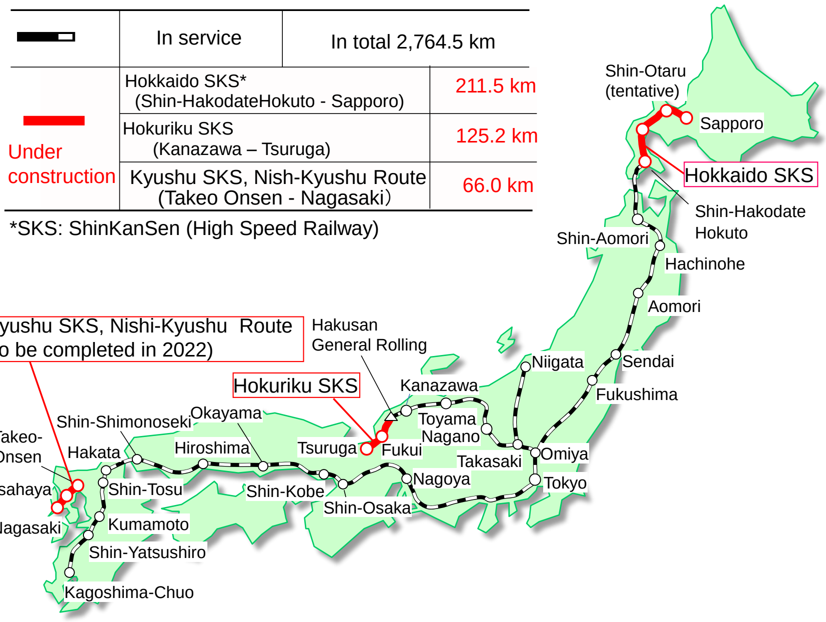


Figure 1. Network of High Speed Railway (ShinKanSen, SKS), as of June, 2017.

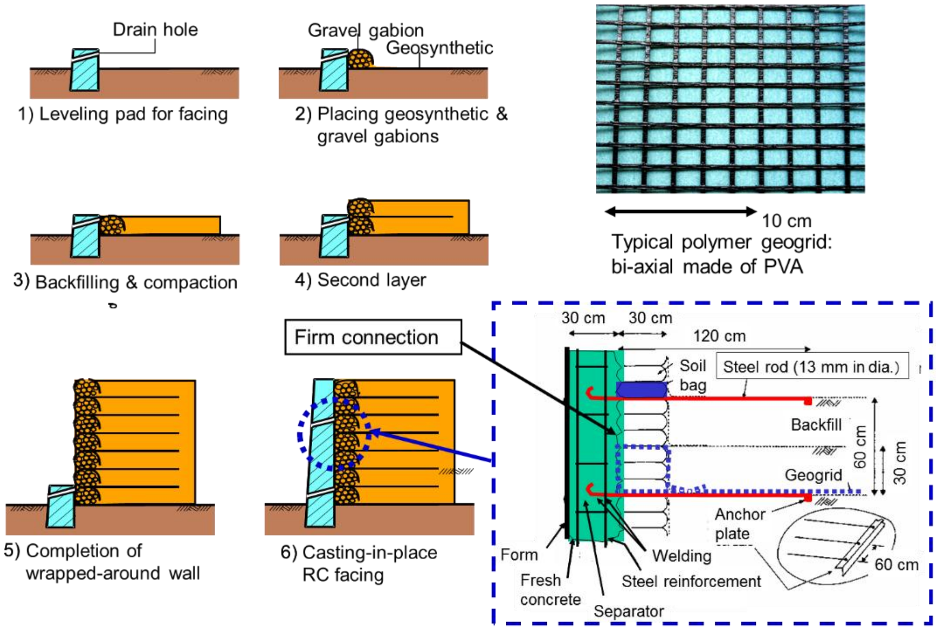


Figure 2. Staged-construction and structure of GRS RW with FHR facing (Tatsuoka et al., 1997, 2014a).

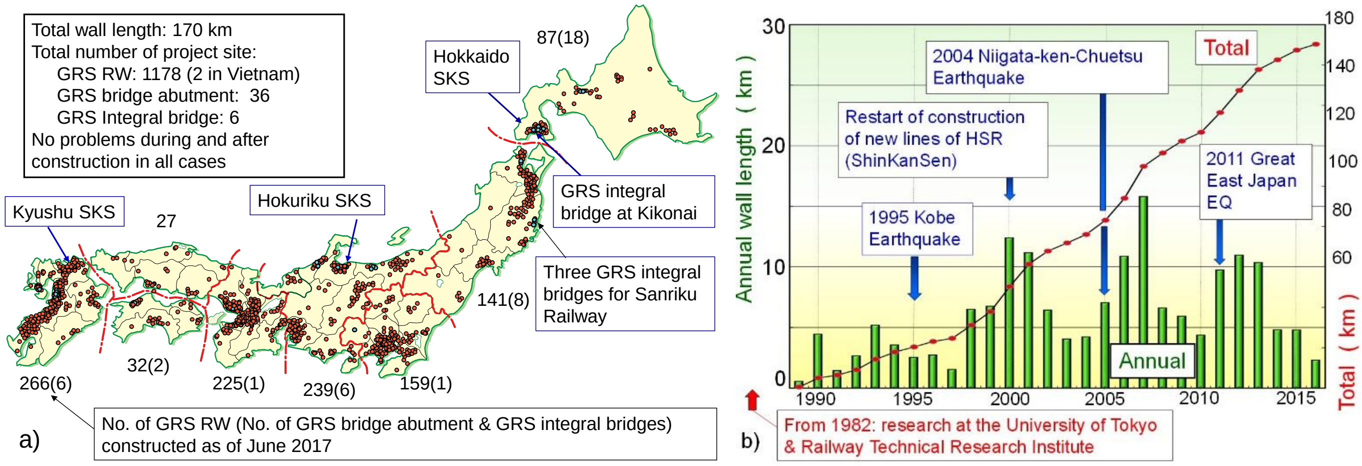


Figure 3. a) Locations; and b) statistics of GRS structures constructed as of June, 2017.

A high seismic stability of this type of GRS RW was validated by its good performance during the 1995 Great Kobe Earthquake (Tatsuoka et al., 1997, 1998). Based on this lesson and results of a comprehensive series of research, the seismic design of GRS structures was developed to have a similar stability as other type structures (i.e., bridges, viaducts, box culverts and tunnels) against such high seismic loads as experienced during that earthquake (Tatsuoka et al., 2014b; Koseki et al., 2007). This seismic design was validated by quite satisfactory performance of many GRS RWs designed following this method during the 2011 Great East Japan Earthquake and the 2016 Kumamoto Earthquake in Kyushu. Moreover, a number of GRS RW of this type were constructed replacing conventional type RWs that collapsed by not only earthquakes but also scouring during flooding. Besides, continuous RC roadbed is more advantageous than conventional ballasted roadbed for very low life cycle maintenance cost despite relatively high construction cost. With HSRs in Japan, continuous RC roadbed was employed first only on RC viaducts and bridges, but not on ordinary embankments. In the meantime, it was confirmed that GRS RWs (Fig. 2) exhibit very small residual settlement while GRS RWs approaching bridge abutments, box culverts and viaducts do not exhibit any a bump, which is often a serious problem with conventional type approach fills. Now, the construction of continuous RC roadbed on GRS RWs of this type is the standard practice for HSRs in Japan. As a result, this type of GRS RW (Fig. 2) is now the standard RW type for railways basically replacing conventional type cantilever RC RWs in new construction (Tatsuoka et al., 2014a). In March 2018, three HSRs are under construction (Fig. 1). This paper outlines the design and construction of many GRS structures adopted for Kyushu SKS Nishi-Kyushu Route (Fig. 4a), most densely ever.

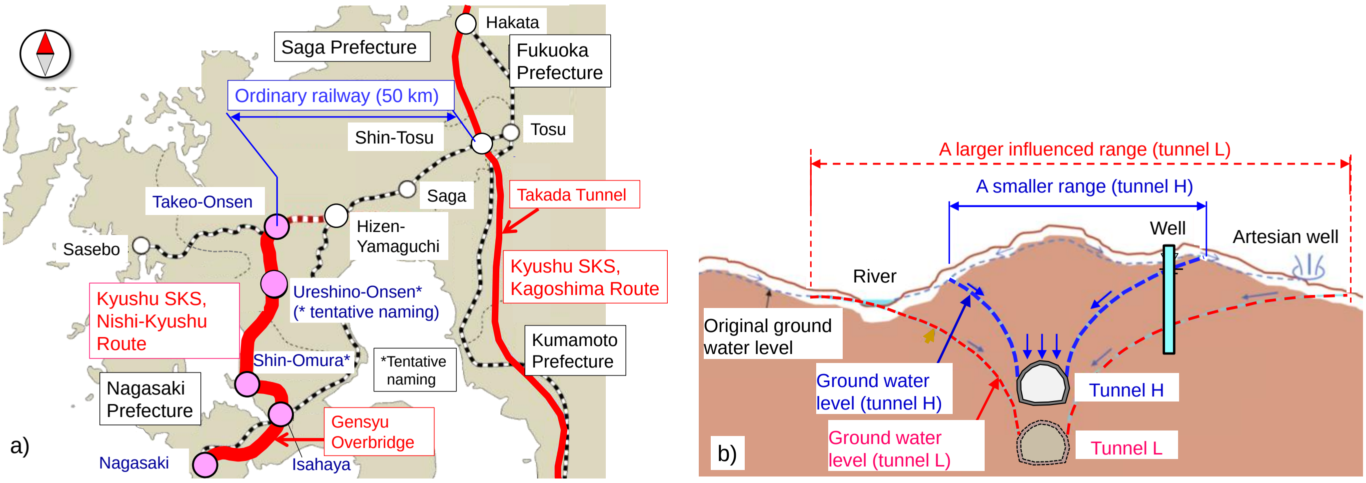


Figure 4. a) Kyushu ShinKanSen, Kagoshima & Nishi-Kyushu Routes; and b) rising of tunnel level.

2 GRS STRUCTURES FOR KYUSHU SHINKANSEN NISHI-KYUSHU ROUTE

2.1 *General*

As this route runs mainly in mountainous areas (Fig. 5), the ratio of the total tunnel length to the total route length (66 km) is very high, about 61 % (Table 1b). Besides, to reduce as much as possible the impact by tunnel construction to the aquatic environment in these mountain areas, the elevation of the tunnels was raised as much as high (Fig. 4b), which reduced the total tunnel length but increased the total number of tunnel, resulting in the highest tunnel number per length (N/L), about 0.47/km, among the recent three HSR projects (Table 1a). Then, the total number of tunnel entrances, bridges, viaducts and embankments located in valleys between adjacent tunnel entrances became very large, which increased the number of GRS structures (Table 1c), basically in place of conventional type structures.

2.2 *GRS RWs*

Of a total length of about 5 km along Nishi-Kyushu Route, GRS RWs with FHR facing (Fig. 2) will be constructed for a length of about 1.7 km to retain the embankment for Omura general rolling stock depot. GRS RWs of this type will be also constructed on both sides of the embankments approaching tunnel entrances at many other sites.

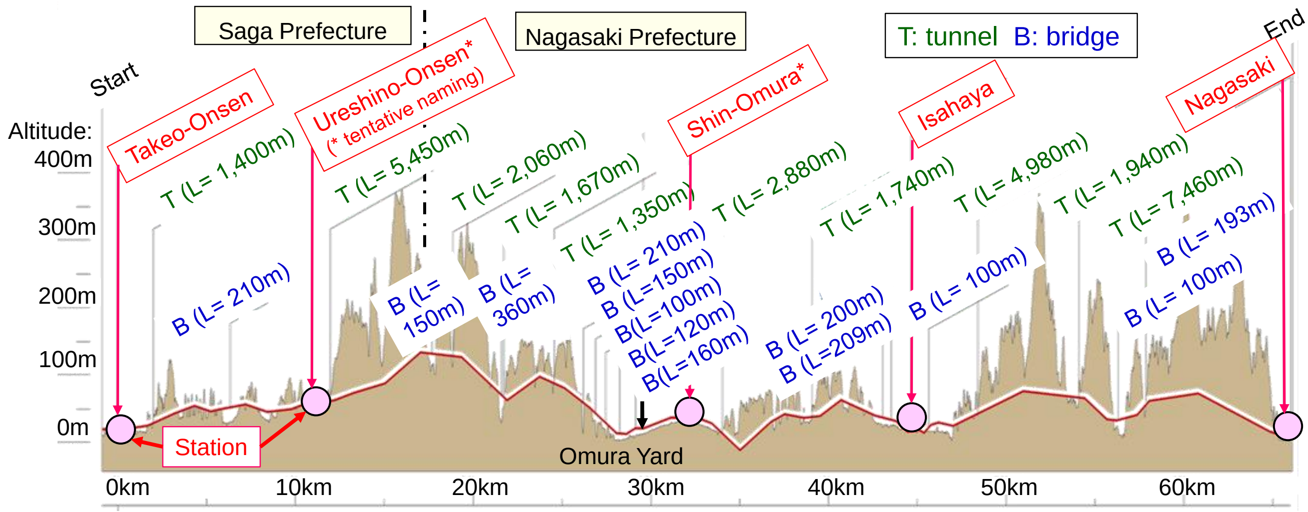


Figure 5. Locations of stations, bridges and tunnels along Kyushu SKS Nishi-Kyushu Route.

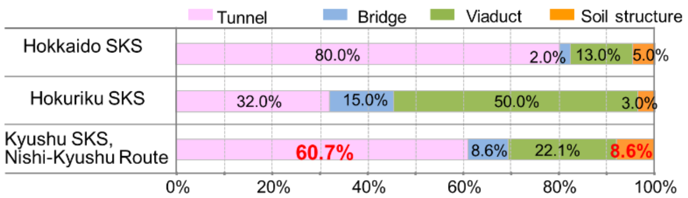
Table 1. Latest three HSR projects in Japan: a) the total number and the number per length of tunnel; and b) length ratios of different type structures; and c) GRS structures for Kyushu SKS Nishi-Kyushu Route.

a)

	Length	No. of tunnel	No. of tunnel per length
Hokkaido SKS* (Shin-Hakodate Hokuto- Sapporo)	211.5 km	19	0.09 /km
Hokuriku SKS (Kanazawa – Tsuruga)	125.2 km	20	0.18 /km
Kyushu SKS, Nishi-Kyushu Route (Takeo-Onsen - Nagasaki)	66.0 km	31	0.46 /km

*SKS: Abbreviation of ShinKanSen (High Speed Railway)

b)



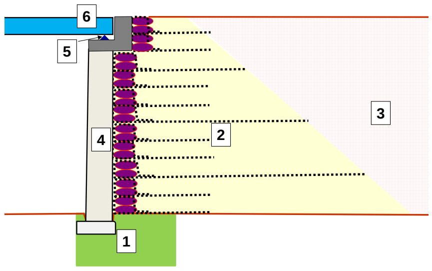
c)

		Saga Pref.	Nagasaki Pref.	Total
①	GRS RW with FHR facing	1,009 m	3,979 m	4,988 m
②	GRS tunnel entrance protection	15	40	55*
③	GRS bridge abutment	34	46	80
④	GRS integral bridge	2	5	7

* 89 % of the total tunnel entrance protections (62)

2.3 *GRS bridge abutments*

GRS bridge abutment (Fig. 6a) can alleviate the following several problems with conventional simple girder bridges (Tatsuoka et al., 2004, 2005): i.e., 1) needs for a massive abutment as a cantilever structure resisting large earth pressure from the unreinforced backfill, often supported by a pile foundation; and 2) a low stability of the approach fill, in particular against earthquakes, developing a bump immediately behind the abutment, and floods. For a high seismic stability and a continuous increase from zero in the thickness of unbound fill behind (zone 3), GRS bridge abutment (Fig. 6a) comprises an approach block (zone 2) of well-compacted lightly cement-mixed well-graded gravelly soil reinforced with geogrid layers connected to the back of the FHR facing. The shape is trapezoidal with the base wider than the crest.



Construction sequence:
1. Ground improvement (when necessary)
2. Approach block of compacted lightly-cement-mixed gravelly soil reinforced with geogrid layers connected to the facing
3. Unbound fill
4. FHR facing
5. Fixed bearing
6. Simple girder

a)

b)

Figure 6. GRS bridge abutment: a) structure; and b) views during construction on a slope at Sugamuta viaduct.

After the first prototype was constructed in 2002 at Takada along Kysuhu SKS Kagoshima Route (Fig. 4a) (Aoki et al., 2005), 36 have been constructed (Fig. 3a). For Nishi-Kyushu Route, in total 80 GRS bridge abutments were adopted in place of conventional type bridge abutments (Table 1c), many at tunnel entrances. The tallest one is 13.5 m-high. Fig. 6b shows a typical construction, where 1) the natural slope is bench-cut; 2) & 3) an approach block is constructed by compacting lightly cement-mixed gravelly soil in a lift of 15 cm to dry densities at least 95 % of the maximum dry density by Modified Proctor; 4) geogrid layers are arranged in the approach block; and 5) & 6) the GRS abutment is completed by constructing FHR facings on the front face and two lateral sides of the approach block.

2.4 *GRS integral bridges*

GRS bridge abutment still uses bearings to support a simple girder. However, bearings are costly for not only installing but also long-term maintenance while vulnerable to seismic loads often with dislodging of the girder. GRS integral bridge (Fig. 7a) alleviates these problems by integrating both ends of a simple girder to the top ends of a pair of FHR facing without using bearings, which makes the girder and facings more slender while more stable than a simple girder bridge comprising GRS bridge abutments (Tatsuoka et al., 2009, 2016; Koda et al., 2013, 2018). As listed in Table 2a, the first prototype was constructed in 2012 for Hokkaido SKS, followed by three for Sanriku Railway completed in 2014 replacing three simple girder bridges that totally collapsed by tsunami of the 2011 Great East Japan Earthquake (Fig. 7b).

a) b)

Figure 7. GRS integral bridge: a) structure & construction; and b) Haipe-sawa bridge, 60 m-long, Sanriku Railway.

Table 2. GRS integral bridges; a) previous major projects (see Fig. 3a); and b) projects for Nishi-Kyushu Route.

Railway	Bridge name	Span	Girder structure	Note
Hokkaido SKS, between Shin-Aomori & Shin-HakodateHokuto stations	Tyugakkousen Overbridge (at Kikonai)	12.00m	RC slab	First prototype
Sanriku Railway (local & ordinary) between Shimanokoshi & Tanohata stations	Matsumaegawa Bridge	27.40m 13.7m+13.7m	RC slab	Continuous girder with two spans
	Koikorobesawa Bridge	39.86m 19.93m+19.93m	RC slab	
	Haipesawa Bridge	60.00m 32.16m+27.84m	SRC* through girder	

a) * Steel-framed steel-reinforced concrete

Location	Bridge name	Span	Girder structure
Between Takeo-Onsen & Ureshino-Onsen stations	Momoki No.1 O.B.+	12.00 m	RC slab
	Tsubakihara O.B.	10.00 m	
Between Ureshino-Onsen & Shin-Omura stations.	Onibashi No.1 O.B. (for a line to Omura General Rolling)	10.10 m	
Between Isahaya & Nagasaki stations	Genshu O.B.*	30.00 m	Pretentioned PC T-shaped main girders
	Genshu Bridge	20.00 m	RC slab
	Kaizu Bridge	15.00 m	
	Funaishi No.4 O.B.	15.00 m	

b) +: over-bridge; * explained in details in this paper.

For Nishi-Kyushu Route, in total seven were adopted (Table 2b), most located in valleys between tunnels. Among them, the over-bridge at Genshu (Fig. 8) comprises four pre-stressed concrete (PC) girders produced and post-tensioned on site and placed on the top ends of the two FHR facings by means a crane. A pair of trapezoidal approach blocks of geogrid-reinforced lightly cement-mixed gravelly soil were designed to be symmetric for simple analysis of in-deterministic forces induced by residual deformation of the girder. The span of Genshu over-bridge is 30 m, which is longest among these seven GRS integral bridges and exceeds the cost-effectively applicable limit of steel-reinforced-concrete (RC) girders for GRS integral bridges. Among relevant other structure types, PC girders are less costly than steel-framed steel-reinforced concrete (SRC) girders (used for Haipesawa Bridge, Fig. 7b). Therefore it is expected that PC girders are frequently used for GRS integral bridges in the future. Unlike RC or SRC girders, the effects of seasonal thermal expansion and contraction, drying shrinkage and creep deformation by prestress of concrete (Fig. 9) on residual steel reinforcement forces (i.e., prestress) in the PC girder should be minimized while restraining the development of tension cracks in the bottom side of the girders. This factor becomes more serious as the span becomes longer. To minimize the residual compressive creep deformation of concrete that would take place after the girder/facing integration, the integration was performed after having allowed sufficient initial creep deformation of concrete to take place and sufficient concrete strength to develop for a period of about 50 – 80 days after the introduction of prestress into the girders, which were performed 3- 4 days after their on-site production. On the other hand, as the approach blocks were constructed on rock foundation, it was not necessary to take into account the effects of their residual displacement on the long-term stress in the girders (i.e., factor 1 in Fig. 9).

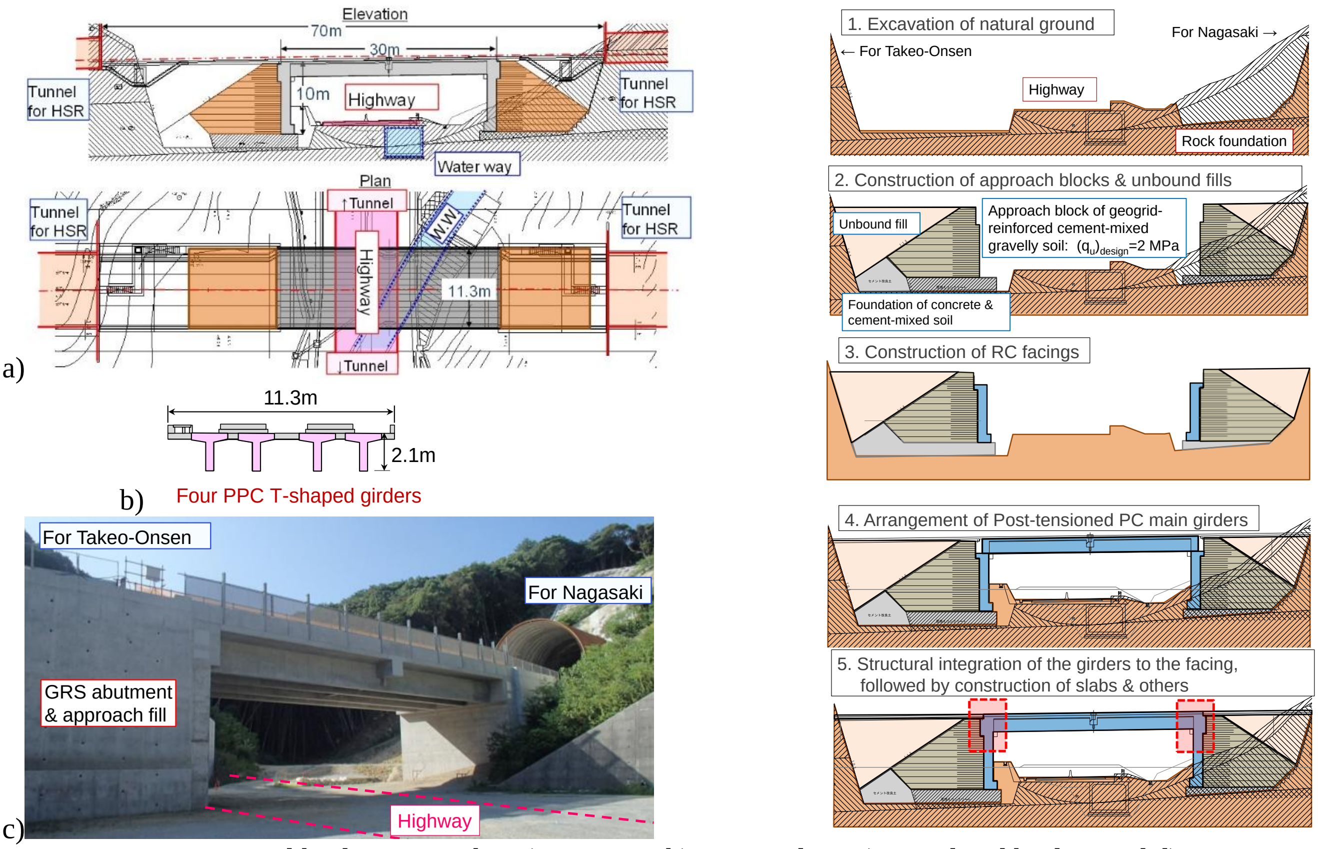


Figure 8. GRS integral bridge at Genshu: a) structure; b) PPC girders; c) completed bridge; and d) construction.

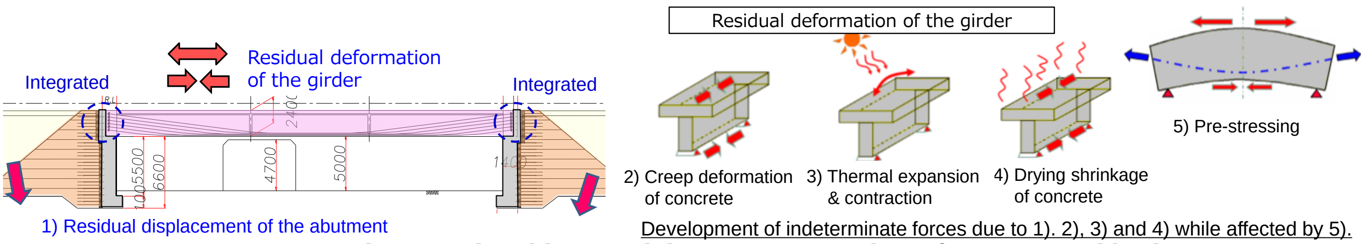


Figure 9. Several potential problems with long span PC girders of GRS integral bridge.

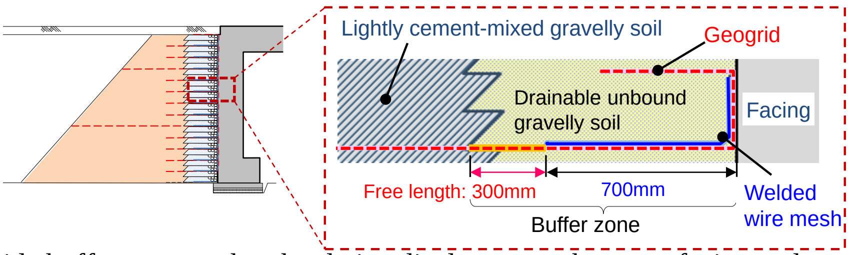


Figure 10. A wide buffer zone to absorb relative displacements between facing and approach block.

Gravel bags at the shoulder of each soil layer of GRS RW (Fig. 2): 1) keep the wall stable during backfill compaction and until the construction of FHR facing; 2) function as a drain of a completed wall; and 3) function as a mechanical buffer that absorbs relative displacements between the facing and the backfill, in particular during severe earthquakes. With GRS integral bridges, this buffer zone comprising unbound gravel should also absorb frequent relative displacements between the FHR facing and the approach blocks of cement-mixed gravelly soil caused by seasonal thermal girder deformation (factor 3 in Fig. 9).

These factors becomes more significant with longer spans. With long GRS integral bridges at Koikorobe-sawa and Haipe-sawa (40 m and 60 m, Table 2a), this buffer zone was 1.0 m-wide (Fig. 10), wider than 30 cm-wide unbound gravel-filled bags for ordinary GRS RWs and 40 cm-wide buffers for shorter GRS integral bridges. As seen from Fig. 10, the buffer zone comprises 70 cm-wide welded metal wire mesh boxes filled with unbound gravelly soil, used in place of geogrid bags for more efficient construction, and a 30 cm-wide free zone of unbound gravelly soil. Acceptable performance of this buffer zone against seasonal frequent and seismic larger relative displacements was confirmed by performing full-scale cyclic loading tests (Tatsuoka et al., 2016; Koda et al., 2017, 2018). This buffer zone (Fig. 10) was also adopted for Genshu Bridge with a span of 30 m. The performance of Genshu Bridge has been monitored since the start of construction to confirm the relevance of the design and construction procedures employed.

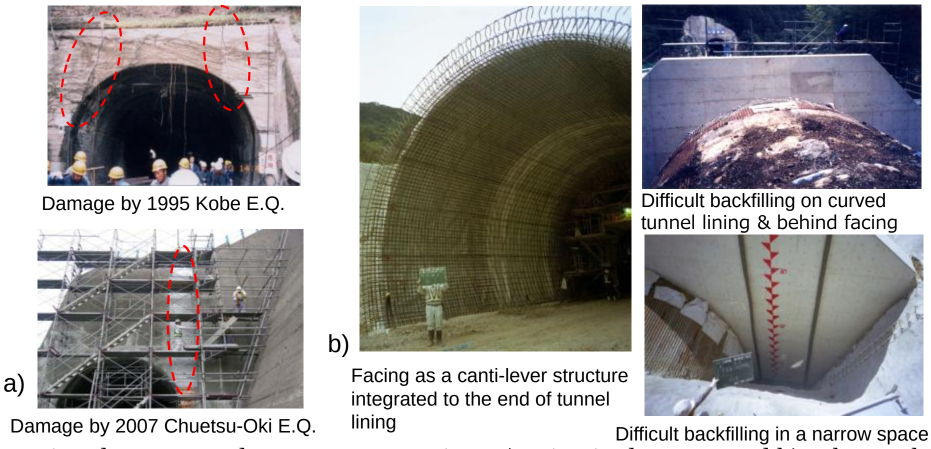


Figure 11. Conventional type tunnel entrance protection: a) seismic damage; and b) other technical problems.

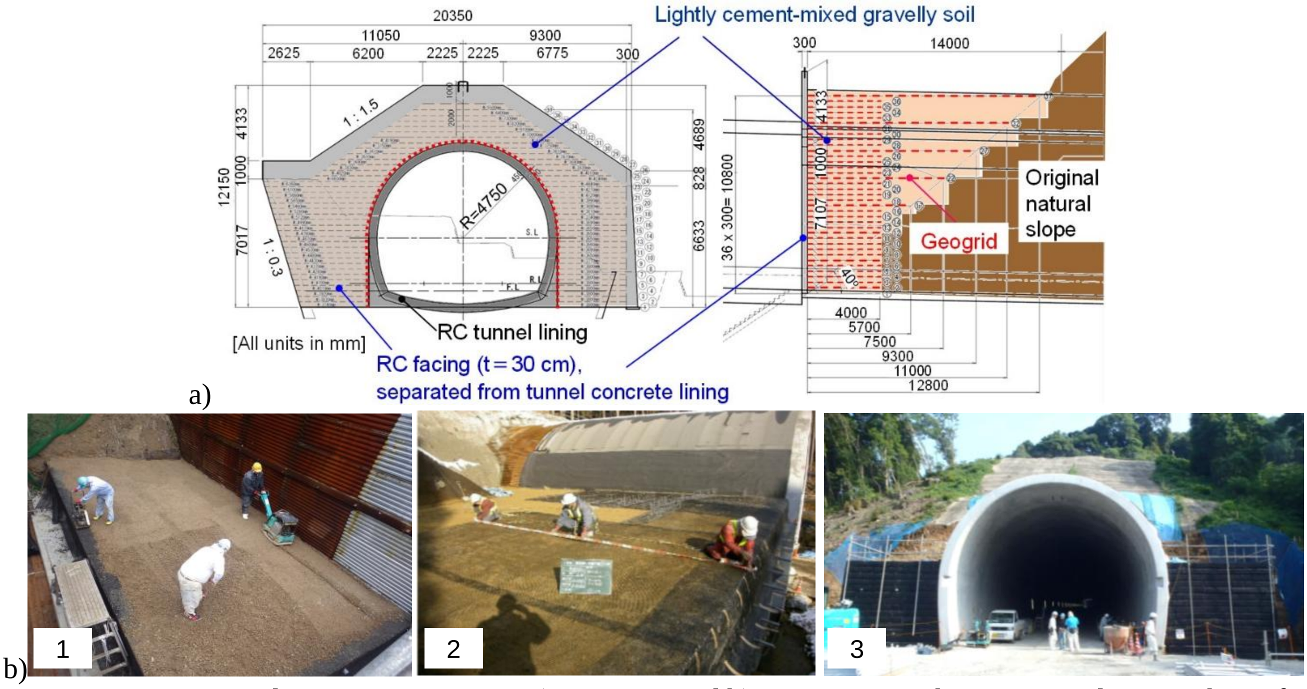


Figure 12. GRS tunnel entrance protection: a) structure: and b) construction, Shiozuru tunnel, Nagasaki Pref.

Figure 13. GRS tunnel entrance protection and GRS bridge abutment, Tawarazaka, Nagasaki Prefecture side.

2.5 *GRS tunnel entrance protections*

Relevant tunnel entrance structures are necessary for railways, in particular for HSRs: 1) to protect the end section of the tunnel lining; 2) to stabilize the natural slope immediate above; and 3) to protect trains against falling rocks and sliding soil masses by severe earthquakes, heavy rains, etc. For Nishi-Kyushu Route, this type of structure are necessary at 62 sites. With the conventional type (Fig. 11), the front RC facing is a complicated cantilever structure integrated to the end of tunnel lining while supporting covering unbound backfill. Moreover, the backfilling and compaction in narrow zones surrounded by the curved tunnel lining, the facing and the natural slopes is quite difficult (Fig. 11b). Besides, many conventional type structures were damaged by previous earthquakes (Fig. 11a). GRS tunnel entrance protection (Fig. 12a) alleviates these problems and were adopted at 55 sites (i.e., 89 % of all the sites) of Nishi-Kyushu Route (Table 1c). After the natural slope is bench-cut, the tunnel lining is constructed outside the slope, then covered with geogrid-reinforced compacted lightly cement-mixed soil (Fig. 12b) to make the earth pressure on the tunnel lining much smaller than with the conventional type. Fig. 12b-3 shows the front view during construction. Finally, the FHR facing is constructed in the same way as GRS RWs (Fig. 2) while structurally separated from the tunnel lining to prevent damage by their interactions. Fig. 13 shows a special case where a GRS tunnel entrance protection and a GRS bridge abutment were constructed consecutively for them to function as counter weight against a slide in the nearby natural slope.

3 SUMMARY

Higher cost-effectiveness and higher performance of various type GRS structures (i.e., retaining wall, bridge abutment, integral bridge and tunnel entrance protection) than conventional type structures has been validated by many case histories. These GRS structures are now the standard type soil structures for high speed railways (HSRs), as well as ordinary railways, constructed basically in place of conventional type soil structures. A large number of these GRS structures were adopted for a new HSR, Kyushu SKS Nishi-Kyushu Route, most densely ever for railways. Many of them are constructed at entrances of many short tunnels constructed at raised elevations to protect the aquatic environment in the adjacent mountain areas. One of the challenging GRS structures is a GRS integral bridge comprising 30 m-long PC girders.

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